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(54) A method of and apparatus for controlling consolidation of a resinous prepreg laminate assembly to produce a composite material article

(57) An apparatus (10) for controlling the consolidation of a resinous prepreg laminate assembly (22) comprises a temperature sensor (30) located at a predetermined position in the prepreg (22) and a control computer (34) which receives temperature signals from the sensor (30). The computer (34) sends signals to adjust the temperature applied to the prepreg (22) by a heater (18). The computer (34) measures the system response time. The computer (34) has mathematical models of the behaviour of critical process variables as a function of time etc and control rules. The computer (34) uses the critical process variables and measurements of temperature to determine the current state of the prepreg every 6 seconds. Every minute the computer (34) uses the current state of the prepreg and the control rules to predict the future state of the prepreg in a time equal to the system response time, which is 5 to 10 minutes, for different applied rates of increase of temperature and selects the highest rate of increase of temperature which does not violate the rules and sends signals to the heater (18) to apply that rate of increase of temperature for the next time period equal to 1 minute.

Fig.1

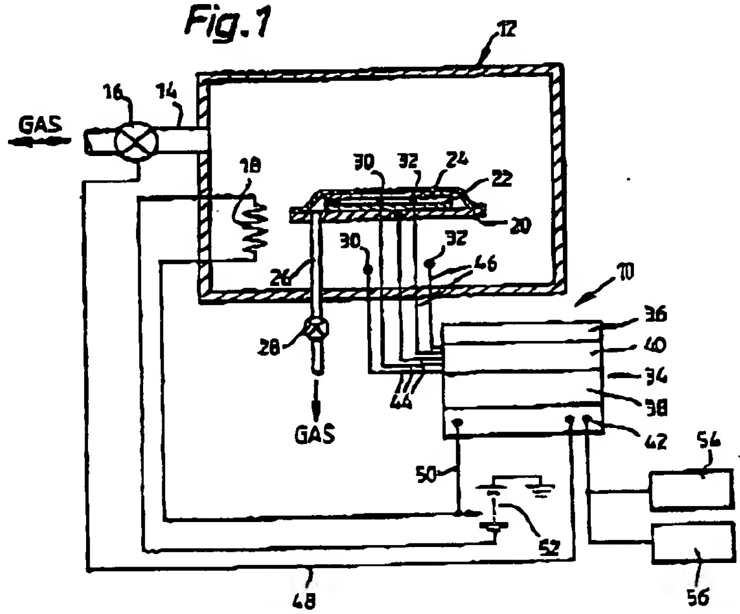

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Fig.1

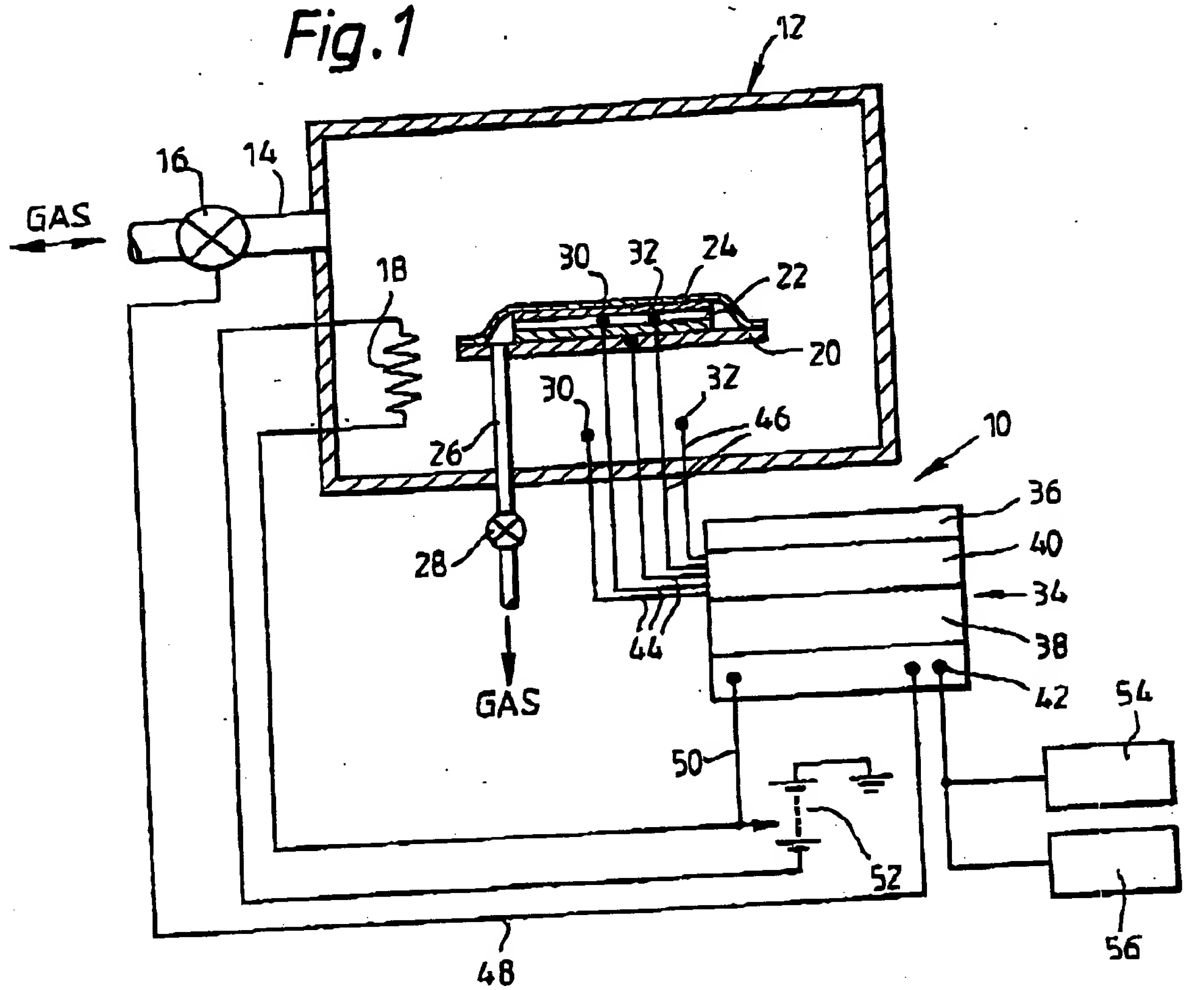
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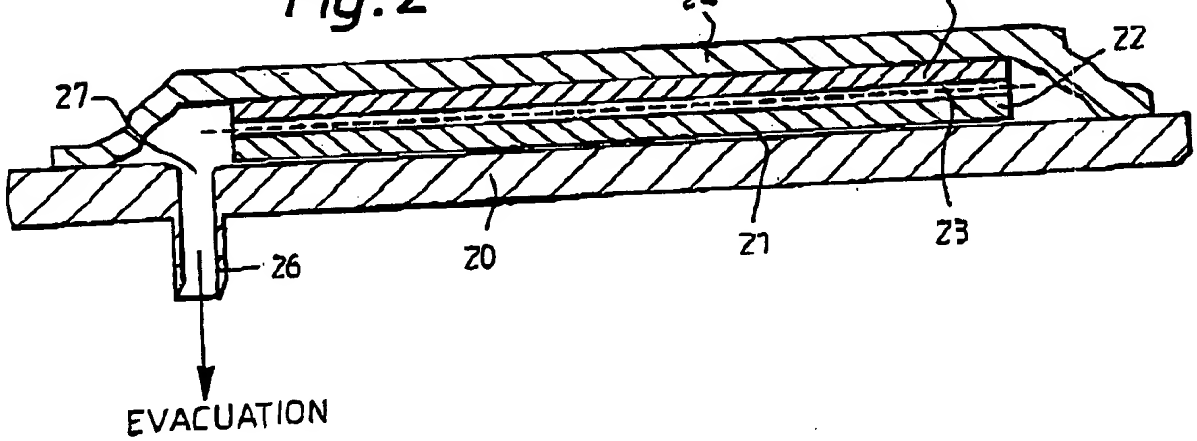
Fig.2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EVACUATION

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Fig.3

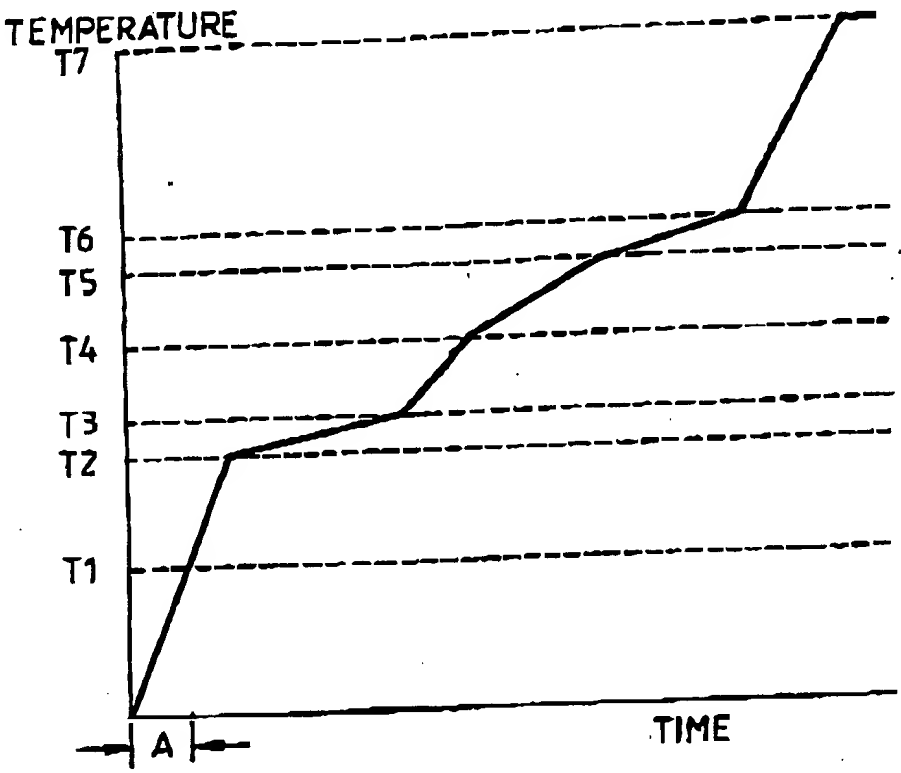

Fig.4

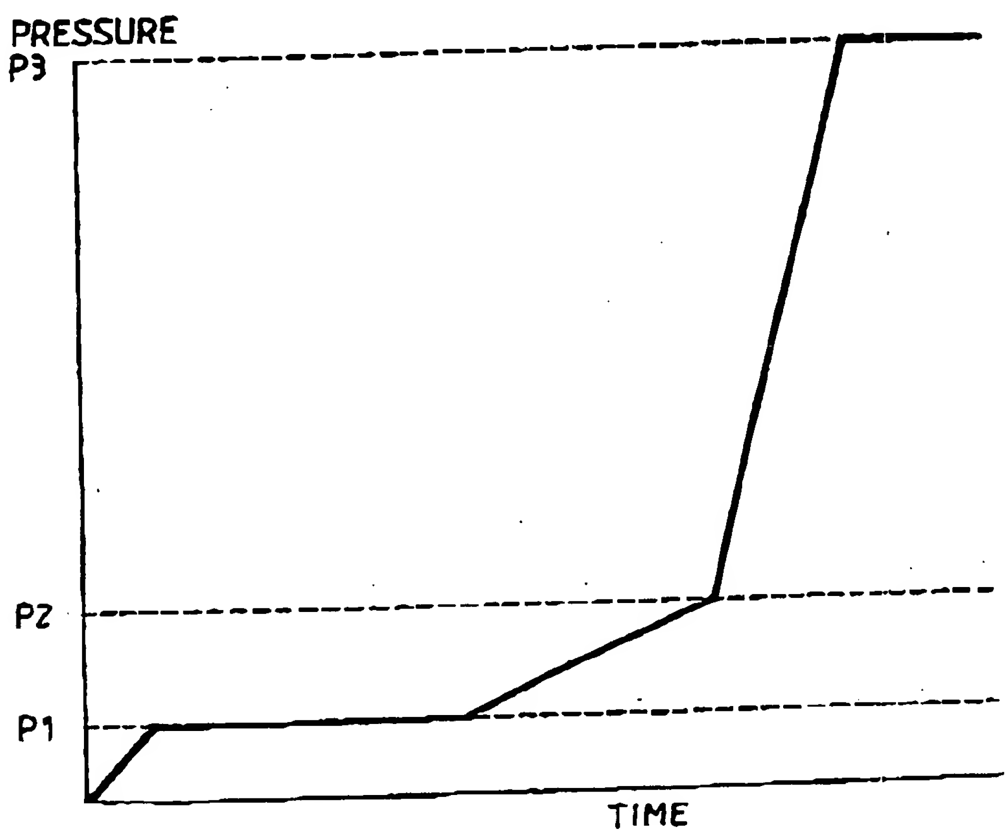

Fig.5A

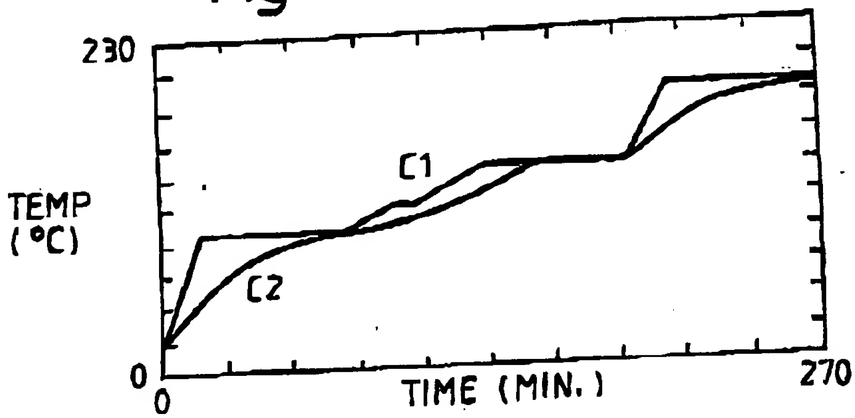

Fig.5B

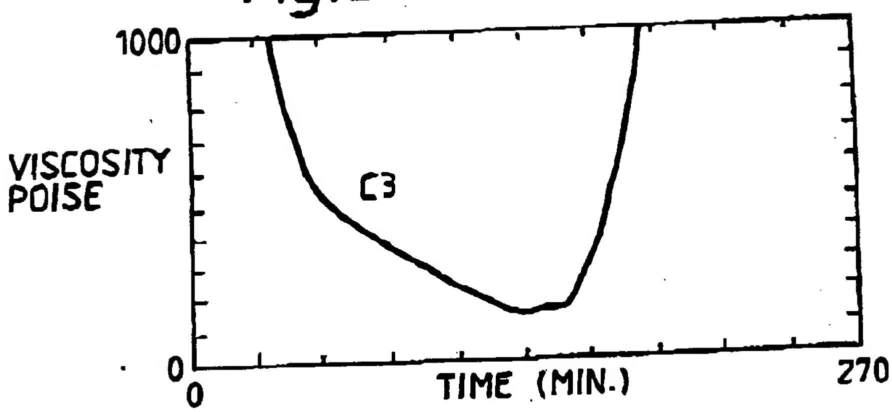

Fig.5C

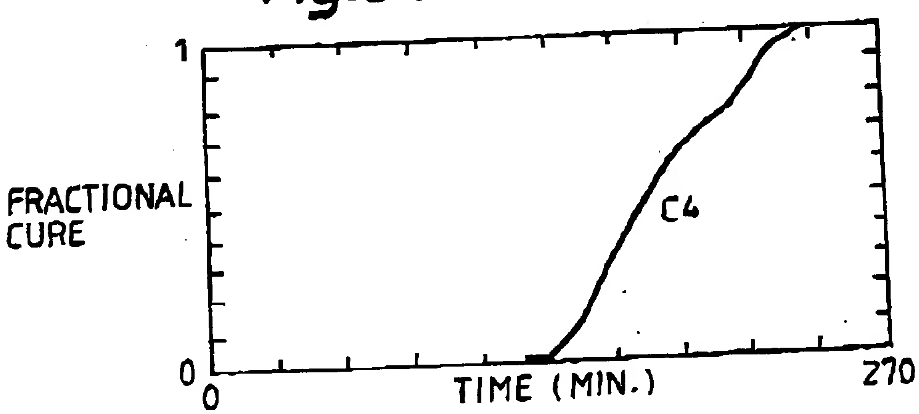

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Fig.5D

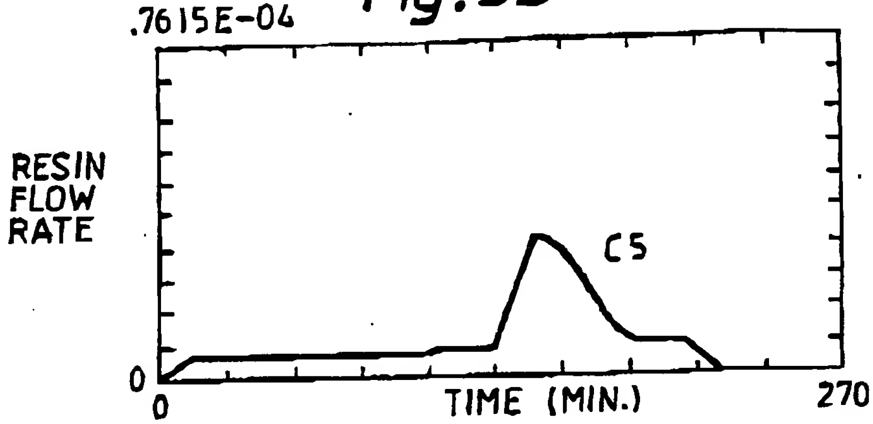

Fig.5E

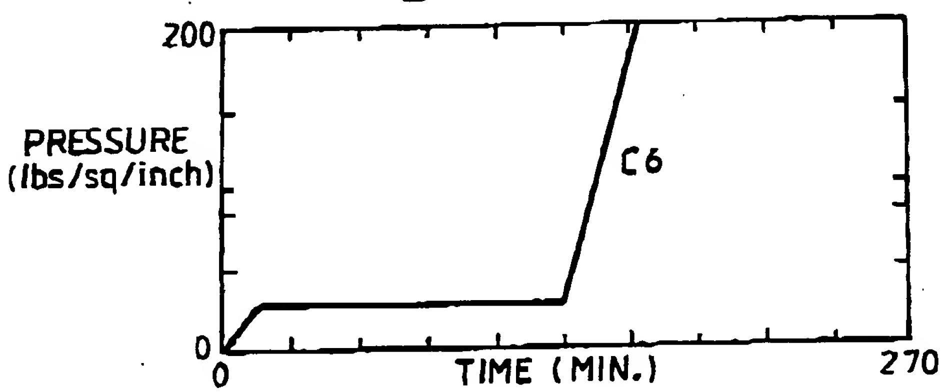

Fig.5F

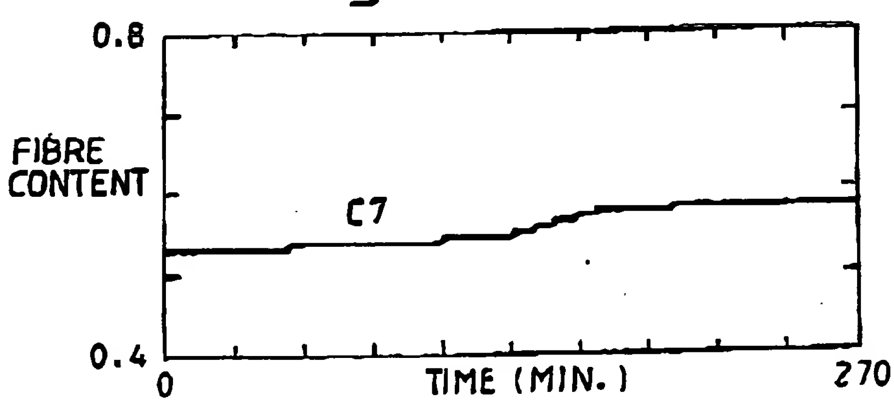

Fig. 6A

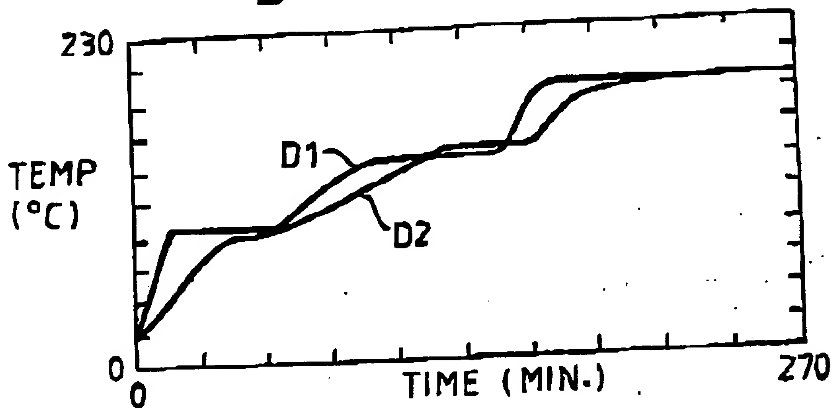

Fig. 6B

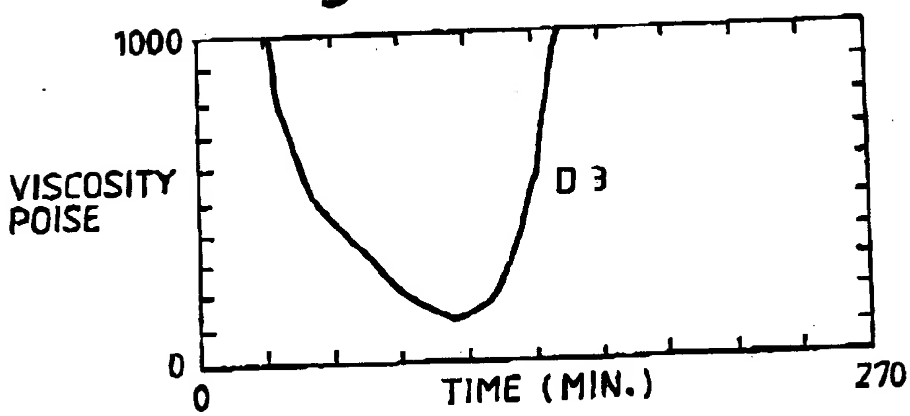

Fig. 6C

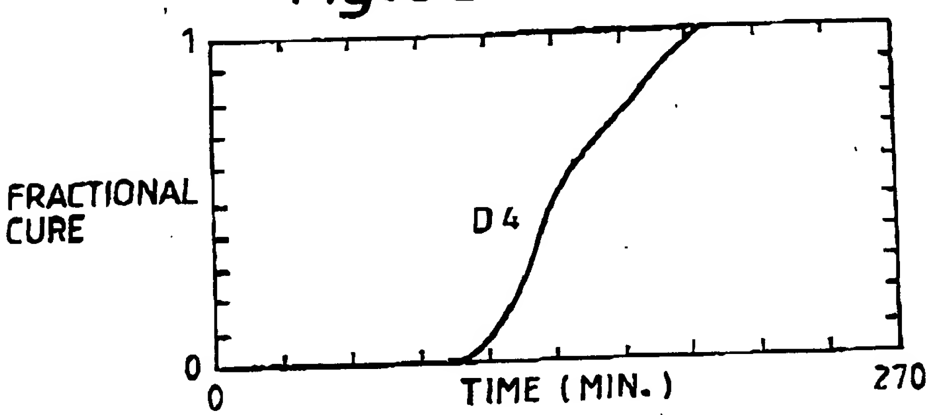

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Fig. 6D

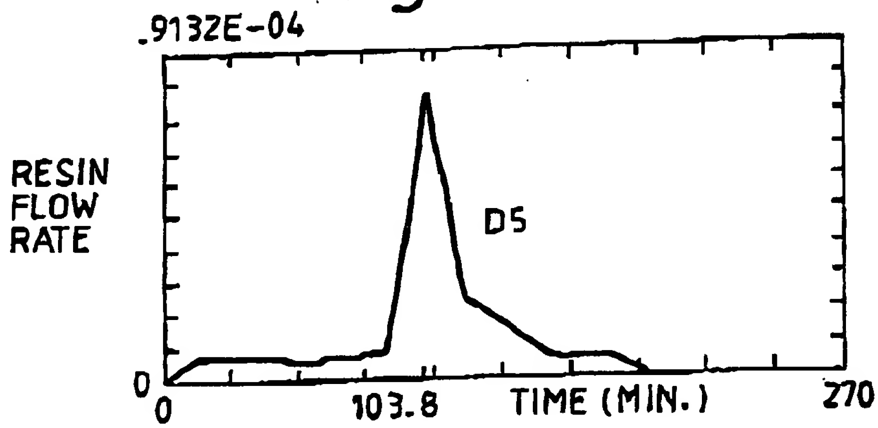


Fig. 6E

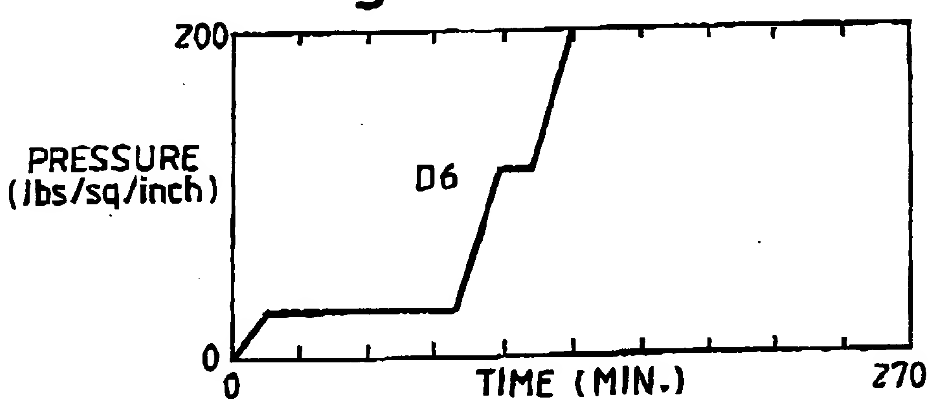
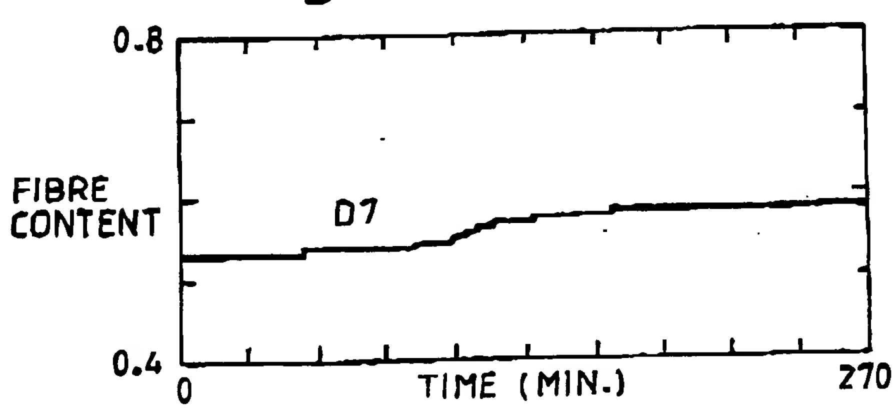


Fig. 6F



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A METHOD OF AND APPARATUS FOR CONTROLLING CONSOLIDATION OF A RESINOUS PREPREG LAMINATE ASSEMBLY TO PRODUCE A COMPOSITE MATERIAL ARTICLE

The present invention relates to a method and apparatus for consolidating a fibre reinforced resin matrix composite material.

In the consolidation of fibre reinforced resin matrix composite materials the consolidation cycle is generally predetermined by means of preset temperature ramps and preset isothermal holding conditions specific only to the material combination being moulded. The application of temperature and the application of pressure in the consolidation cycle follow experimentally predetermined paths.

Heat transfer through a lay up of resinous prepreg laminates is however dependent on both the materials of the constituent layers in the lay up and upon the mould on which the lay up is placed. The heat transfer is particularly dependent upon the mould and the thickness of the individual resinous prepreg laminates. The thickness and thermal properties of the resinous prepreg laminates have a major influence on the manner in which the exothermic heat of reaction is dissipated during the moulding/consolidation cycle. This is a necessary consideration if an exotherm damage free composite material is to be produced.

The control of cure and hence resin viscosity by temperature control is necessary if the flow of excess resin out of the resinous prepreg laminates is to be maintained for a sufficient length of time for the fibrous layers to collapse to the required final composite thickness with, ideally, zero void content in the resulting component or artefact.

It is for these reasons that an individual lay up of resinous prepreg laminates will have associated with it, its own unique moulding/consolidating cycle. Therefore by the use of standard moulding/consolidating cycles, as

is current practice, composite material with the best physical properties is not necessarily produced nor is the moulding/consolidating effected in the most cost effective manner, i.e. in the shortest time possible.

The present invention seeks to provide a novel method and apparatus for consolidating a fibre reinforced resin matrix composite.

Accordingly the present invention provides a method of controlling the consolidation of a resinous prepreg laminate assembly to produce a composite material article comprising:-

(a) applying heat, at a predetermined rate of increase of temperature, to the resinous prepreg laminate assembly and calculating the time taken for the temperature to increase at a plurality of positions in the resinous prepreg laminate assembly, selecting the greatest calculated time as the system response time or calculating the time taken for the temperature to increase at a position at, or near, the centre of the resinous prepreg laminate assembly, selecting the calculated time as the system response time,

(b) providing mathematical models of the behaviour of at least some of the critical process variables as functions of time, and/or as functions of temperature and/or as functions of other critical process variables,

(c) providing rules to control the application of heat to the resinous prepreg laminate assembly,

(d) calculating the temperature distribution, the amount of resin cure, the viscosity of the resin, the rate of heat generation due to reaction at each of the plurality of positions throughout the resinous prepreg laminate assembly and the amount of consolidation of the resinous prepreg laminate assembly due to outflow of resin, at successive ones of a first series of time intervals having a first predetermined duration, using the mathematical models in (b),

(e) determining the rate of increase of temperature

to be applied to the resinous prepreg laminate assembly for a future time interval having a second predetermined duration, at successive ones of a second series of time intervals having a third predetermined duration, using the data collected in step (d), the mathematical models in step (b) and the rules in step (c), wherein the second predetermined duration is greater than the first predetermined duration, the third predetermined duration is greater than the first predetermined duration, and the system response time is greater than either the second predetermined time interval or the third predetermined time interval,

(f) predicting the course of the process for a future time interval equal to the system response time for a plurality of selected rates of increase of temperature,

(g) discarding any selected rates of increase of temperature, which are predicted to produce unacceptable temperature increases, temperature distributions, viscosities and consolidation,

(h) selecting the highest rate of increase of temperature which is predicted to produce acceptable temperature increases, acceptable temperature distributions, acceptable viscosities and acceptable consolidation,

(i) applying the selected highest rate of increase of temperature to the resinous prepreg laminate assembly for a time interval having the second predetermined duration, which highest rate of increase of temperature is predicted to produce acceptable temperature increase, acceptable temperature distributions, acceptable viscosities and acceptable consolidation for a next future time interval equal to the system response time, at successive ones of the second series of time intervals.

Preferably the first predetermined duration is 6 seconds.

Preferably the second predetermined duration is 60 seconds.

Preferably the third predetermined duration is 60 seconds.

Preferably the resinous prepreg laminate assembly being cured contains carbon fibres.

Preferably the resinous prepreg laminate assembly being cured contains an epoxy resin.

The temperature may be measured at at least one predetermined position in the resinous prepreg laminate assembly.

If the resinous prepreg laminate assembly is placed upon a mould, the temperature may be measured at at least one predetermined position in the mould.

If the resinous prepreg laminate assembly is placed in an autoclave, the temperature of the gas within the autoclave, may be measured.

The method may comprise comparing the measured temperature with the calculated temperature at successive ones of the second series of time intervals prior to selection of the highest rate of increase of temperature to the resinous prepreg laminate assembly, determining if any difference between the measured temperature and the calculated temperature is within a predetermined range to check that the rules are accurate.

The method may comprise applying sufficient pressure to the resinous prepreg laminate assembly to maintain thermal contact for efficient heat transfer until the reaction occurs, increasing the pressure applied to the resinous prepreg laminate assembly in steps to cause the resin to flow out of the resinous prepreg laminate assembly when the reaction occurs.

The method may comprise measuring the pressure applied on the resinous prepreg laminate assembly at at least one predetermined position in the resinous prepreg laminate assembly.

If the resinous prepreg laminate assembly is placed

in an autoclave, the method may comprise measuring the pressure of the gas within the autoclave.

The method may comprise comparing the measured pressure with the calculated pressure at successive ones of the second series of time intervals prior to selection of the highest rate of increase of pressure to the resinous prepreg laminate assembly, determining if any difference between the measured pressure and the calculated pressure is within a predetermined range to check that the rules are accurate.

The present invention also provide an apparatus for controlling the consolidation of a resinous prepreg laminate assembly to produce a composite material article comprising:-

pressing means to apply a pressure on the resinous prepreg laminate assembly,

heating means to heat the resinous prepreg laminate assembly,

a control computer having means to calculate the time taken for the temperature to increase at a plurality of positions in the resinous prepreg laminate assembly from the commencement of application of heat on the resinous prepreg laminate assembly, or to calculate the time taken for the temperature to increase at a position at, or near, the centre of the resinous prepreg laminate assembly,

the control computer having means to select the greatest calculated time as the system response time, or to select the calculated time as the system response time,

the control computer having mathematical models of the behaviour of at least some of the critical process variables as functions of time, and/or as functions of temperature and/or as functions of other critical process variables,

the control computer having rules to control the application of heat to the resinous prepreg laminate

assembly,

the control computer having means for calculating the temperature distribution, the amount of resin cure, the viscosity of the resin, the rate of heat generation due to reaction at each of the plurality of positions throughout the resinous prepreg laminate assembly and the amount of consolidation of the resinous prepreg laminate assembly due to outflow of resin, at successive ones of a first series of time intervals having a first predetermined duration, using the mathematical models,

the control computer having means to determine the rate of increase of temperature to be applied to the resinous prepreg laminate assembly for a future time interval having a second predetermined duration, at successive ones of a second series of time intervals having a third predetermined duration, using the calculated values of temperature distribution, the amount of resin cure, the viscosity of the resin, the rate of heat generation at each of the positions in the resinous prepreg laminate assembly and the amount of consolidation, the mathematical models and the rules, the second predetermined duration is greater than the first predetermined duration, the third predetermined duration is greater than the first predetermined duration, and the system response time is greater than either the second predetermined time interval or the third predetermined time interval,

the control computer having means for predicting the course of the process for the next future time interval equal to the system response time for a plurality of selected rates of increase of temperature, the control computer having means to discard any selected rates of increase of temperature which are predicted to produce unacceptable temperature increases, temperature distribution, viscosities and consolidation, the control computer having means for selecting the highest rate of increase of temperature which is predicted to produce

acceptable temperature increases, acceptable temperature distributions, acceptable viscosities and acceptable consolidation of the resinous prepreg laminate assembly,

the control computer having means for sending a signal to the heating means to apply the selected highest rate of increase of temperature to the resinous prepreg laminate assembly for the next future time interval equal to the second predetermined duration at successive ones of the second series of time intervals.

At least one temperature sensor may be located at a predetermined position in the resinous prepreg laminate assembly, means to supply temperature signals from the at least one temperature sensor to the control computer during the curing process.

If the resinous prepreg laminate assembly may be placed upon a mould, at least on temperature sensor may be located at a predetermined position in the mould, means to supply temperature signals from the at least one temperature sensor to the control computer during the curing process.

If the resinous prepreg laminate assembly is placed in an autoclave, at least one temperature sensor may be located in the autoclave to measure the temperature of a gas in the autoclave, means to supply temperature signals from the at least one temperature sensor to the control computer during the curing process.

The control computer may have means for comparing the measured temperature with the calculated temperature at every third predetermined duration prior to selection of the highest rate of increase of temperature to the resinous prepreg laminate assembly, the comparing means determines if any difference between the measured temperature and the calculated temperature is within a predetermined range to check that the rules are accurate.

A plurality of temperature sensors may be provided.

The at least one temperature sensor may be a thermocouple.

The pressing means may apply sufficient pressure to the resinous prepreg laminate assembly to maintain thermal contact for efficient heat transfer until the reaction occurs, and increases the pressure applied to the resinous prepreg laminate assembly in steps to cause the resin to flow out of the resinous prepreg laminate assembly when the reaction occurs.

There may be at least one pressure sensor at a predetermined position in the resinous prepreg laminate assembly, means to supply pressure signals from the at least one pressure sensor to the control computer during the curing process.

If the resinous prepreg laminate assembly is placed in an autoclave, at least one pressure sensor may be placed in the autoclave to measure the pressure of the gas in the autoclave, means to supply pressure signals from the at least one pressure sensor to the control computer during the curing process.

The control computer may have means for comparing the measured pressure with the calculated pressure at every third predetermined time period prior to selection of the highest rate of increase of pressure to the resinous prepreg laminate assembly, determining if any difference between the measured pressure and the calculated pressure is within a predetermined range to check that the rules are accurate.

The pressing means may comprise means to supply pressurised gas.

The present invention will be more fully described by way of example with reference to the accompanying drawings, in which:-

Figure 1 is an apparatus for controlling the application of heat and pressure during the curing of a resinous prepreg laminate assembly according to the present invention.

Fig 2 is a longitudinal cross-sectional view through a resinous prepreg laminate assembly.

Fig 3 is a graph of the temperature applied to the resinous prepreg laminate assembly against time.

Fig 4 is a graph of the pressure applied to the resinous prepreg laminate assembly against time.

Fig 5A is a graph of the temperature applied to a resinous prepreg laminate assembly against time for a steel mould.

Fig 5B is a graph of the viscosity of the resin in the resinous prepreg laminate assembly against time for a steel mould.

Fig 5C is a graph of the fractional cure of the resinous prepreg laminate assembly against time for a steel mould.

Fig 5D is a graph of the resin flow rate out of the resinous prepreg laminate assembly against time for a steel mould.

Fig 5E is a graph of the pressure applied to the resinous prepreg laminate assembly against time for a steel mould.

Fig 5F is a graph of the fibre content of the resinous prepreg laminate assembly against time for a steel mould.

Fig 6A is a graph of the temperature applied to a resinous prepreg laminate assembly against time for a ceramic mould.

Fig 6B is a graph of the viscosity of the resin in the resinous prepreg laminate assembly against time for a ceramic mould.

Fig 6C is a graph of the fractional cure of the resinous prepreg laminate assembly against time for a ceramic mould.

Fig 6D is a graph of the resin flow rate out of the resinous prepreg laminate assembly against time for a ceramic mould.

Fig 6E is a graph of the pressure applied to the resinous prepreg laminate assembly against time for a ceramic mould.

Fig 6F is a graph of the fibre content of the resinous prepreg laminate assembly against time for a ceramic mould.

An apparatus 10 for controlling the application of heat and pressure to a resinous prepreg laminate assembly 22 to form a composite material is shown in figure 1. The apparatus 10 comprises an autoclave 12 which has a pipe 14 connected to the interior of the autoclave 12. A pump 16 is located in the pipe 14 to control the supply of pressurising gas to the interior of the autoclave 12. An electrical heater 18 is positioned within the autoclave 12 to apply heat to the resinous prepreg laminate assembly 22. The resinous prepreg laminate assembly 22, shown more clearly in figure 2, is arranged on a rigid former 20, which is positioned within the autoclave 12. The rigid former 20 is shown to be flat in figures 1 and 2, but in practice is shaped to define the required component/article shape. The rigid former 20 must remain rigid during the moulding cycle, the thermal expansion of the rigid former 20 preferably matches the thermal expansion of the composite component/article being formed to minimise thermally induced distortions and the thermal capacity of the rigid former 20 preferably is minimised to enable controlled and rapid temperature increases to be achieved for economic moulding cycles. The rigid former 20 is preferably constructed from thin stainless steel members or, alternatively from graphite reinforced plastic members.

A release layer 21 is positioned between the rigid former 20 and the resinous prepreg laminate assembly 22 to facilitate the removal of the moulded composite component following the curing of the resinous prepreg laminate assembly 22 as shown in figure 2.

A porous release layer 23 is positioned on top of the resinous prepreg laminate assembly 22, a bleed pack 25 is positioned on top of the porous release layer 23 and a membrane 24 is positioned over the bleed pack 25

and is sealed at its edges to the rigid former 20, as shown in figure 2. The porous release layer 23 initially allows the escape of excess resin from the resinous prepreg laminate assembly 22 into the bleed pack 25 but subsequently allows the filled bleed pack 25 and the composite component to be parted following curing of the resinous prepreg laminate assembly 22. The bleed pack 25 comprises a number of glass cloth plies the total porosity of which is sufficient to absorb only the excess resin calculated to be present in the resinous prepreg laminate assembly 22. The bleed pack 25 is isolated from a further glass cloth breather layer by an impervious membrane. The membrane 24 preferably comprises a silicone rubber sheet. The rigid former 20 and membrane 24 form a sealed chamber in which the resinous prepreg laminate assembly 22 is positioned. The rigid former 20 has a port 27 connected to a vacuum pump 28 by a pipe 26 to enable gas, e.g. air, to be removed from the sealed chamber during the moulding cycle.

The resinous prepreg laminate assembly 22 is consolidated by supplying a suitable gas, for example nitrogen, into the autoclave 12 <u>via</u> pipe 14, heating the gas by heaters 18 and circulating the gas throughout the autoclave 12 in order to raise the temperature of the resinous prepreg laminate assembly 22. Pressure is applied to the resinous prepreg laminate assembly 22 by supplying more gas into the autoclave 12 to increase the pressure of the gas in the autoclave 12. An increase in pressure causes excess fluid resin to be forced out of the resinous prepreg laminate assembly 22 into the bleed pack 25 enabling the resinous prepreg laminate assembly 22 to be consolidated to the desired high fibre volume fraction and to be formed to the shape of the rigid former 20. In order to eliminate or reduce fibre wash and voidage and to achieve uniform consolidation throughout the composite component the pressure and temperature conditions have to be selected to control the

viscosity of the resin.

A t mperature sens r 30, for example a thermocouple, is positioned at a predetermined position in the resinous prepreg laminate assembly 22. In this example the temperature sensor 30 is located at the middle of the resinous prepreg laminate assembly 22. If so desired a number of temperature sensors may be positioned at a number of predetermined positions in the resinous prepreg laminate assembly 22. It may be possible to use three temperature sensors at different locations, one in the middle and one at each side through the thickness of the resinous prepreg laminate assembly to determine the temperature gradient. Preferably the temperature sensor is located in the former 20. It may be possible to use three temperature sensors at different locations, one in the middle and one at each side through the thickness of the mould to determine the temperature gradient. A pressure sensor 32 is positioned at a predetermined position in the resinous prepreg laminate assembly 22. If so desired a number of pressure sensors may be positioned at a number of predetermined positions in the resinous prepreg laminate assembly 22. Preferably the pressure sensor is located in the autoclave 12 to measure the pressure of the gas in the autoclave 12. The temperature sensor 30 and pressure sensor 32 send temperature and pressure signals to a control computer 34 via cables 44 and 46 respectively.

The control computer 34 has a calculator 36 to calculate the time taken from the instant the heater 18 is signalled to change the gas temperature to the instant that each position of the resinous prepreg laminate assembly 22 is affected by the temperature change. The control computer 34 selects the greatest calculated time as the system response time. One point at, or near, the centre of the resinous prepreg laminate assembly will be the last to be affected by the temperature change. The time calculated for the temperature to change at this

position is called the system response time. It may be possible in an alternative embodiment to calculate the time for the temperature to change at, or near, the centre of the resinous prepreg laminate assembly only, and use this as the system response time. The system response time is a measure of the natural temperature response of the particular resinous prepreg laminate assembly. A temperature gradient is produced in the resinous prepreg laminate assembly when heat is applied.

The control computer 34 has mathematical models of the behaviour of all the critical process variables as a function of time, as a function of temperature and as a functions of other critical process variables in a store 38. The critical process variables are the resin cure, the resin viscosity, the resin flow and the rate of extraction of heat generation. All the critical process variables are interdependent e.g. resin viscosity depends upon the amount of resin cure and both of these variables are dependent upon time and temperature.

The control computer 34 also has rules to control the application of heat and pressure on the resinous prepreg laminate in the store 38. The rules are:- excessive temperature rise or thermal runaway conditions, initiated by heat build up within the resinous prepreg laminate assembly 22 due to accelerating exothermic cure reaction, must be avoided otherwise resin degradation will occur and the resulting composite material will have impaired properties. The viscosity of the resin must be minimised to facilitate the flow of resin from the resinous prepreg laminate assembly 22 into the bleed pack 25, and the minimum viscosity condition must be maintained for a sufficient length of time to allow all the excess resin to flow out of the resinous prepreg laminate assembly 22. There must be no excessive thermal gradients in the resinous prepreg laminate assembly 22 otherwise adverse cure and adverse viscosity gradients will be produced resulting in premature arrest of resin

flow out of the resinous prepreg laminate assembly 22. The consolidation pressure must be applied such that uniform resin composition is achieved and local variations in fibre volume fraction is minimised. The total moulding process should be completed in as short a time period as is possible, subject to the previous rules to produce the composite meterial in the most cost effective manner.

The control computer 34 has a calculator 40 which in conjunction with the mathematical models of the critical process variables, at predetermined time periods, determines the temperature distribution at discrete locations throughout the resinous prepreg laminate assembly, determines the amount of resin cure and the resin viscosity for the same locations. These material properties are dependent upon the thermal history of the process up to the current time step. The calculator 40 determines the rate of heat generation due to reaction at each of the locations and determines the amount of consolidation of the resinous prepreg laminate assembly due to outflow of resin into the bleed pack. The calculator 40 determines these parameters, at small first predetermined time intervals, for example every 6 seconds.

The control computer 34 has a second calculator 42 which uses the most up to date values of temperature distribution, resin cure, resin viscosity and rate of heat generation for each of the locations determined by the first calculator 40 in conjunction with the mathematical models and the rules, at further predetermined periods, to select the temperature to be applied to the resinous prepreg laminate assembly 22 during the next, future, second predetermined time period, for example for a 60 second period. The calculator 42 selects the temperature to be applied at third predetermined time intervals, for example every 60 seconds. The calculator 42 predicts the future coarse of

the process if the maximum rate of temperature increase was applied to the resinous prepreg laminate assembly 22 for a future time interval of duration equal to the system response time. The calculator 42 determines if there will be an excessive temperature rise due to heat build up within the resinous prepreg laminate assembly due to accelerating exothermic cure reaction, if there will be too high a viscosity to allow resin to flow out of the resinous prepreg laminate assembly, if there will be excessive thermal gradients in the resinous prepreg laminate assembly and if there will be a non uniform resin composition or too high a variation in fibre volume fraction. If the calculator 42 predicts that the maximum rate of temperature increase will not violate the rules, the control computer 34 sends a control signal to the heater 18 via cable 50 to apply the maximum rate of temperature increase to the resinous prepreg laminate assembly 22 for the next second time time period of 60 seconds. If the calculator 42 predicts that the maximum rate of temperature increase will violate the rules, the calculator 42 repeats the prediction process at the next lowest rate of temperature increase. Eventually the calculator 42 finds a highest rate of temperature increase which will not violate the rules, and the control computer 34 sends a control signal to the heater 18 to apply this rate of temperature increase for the next second predetermined time period of 60 seconds. The highest rate of increase of temperature may be zero. The calculator 42 uses the same procedure to predict and select the pressure to be applied for each next second predetermined time period.

The calculator 42 selects the appropriate temperature and pressures to be applied to the resinous prepreg laminate assembly 22 every 60 seconds up to the time at which the rules determine that the resin is fully cured.

Thus the control computer predicts the maximum safe

rate of increase of temperature, within the system response time, at suitable time periods of the process and this generates a temperature profile for the autoclave/resinous resinous prepreg laminate assembly which results in the quickest and safest way to mould the particular resinous prepreg laminate assembly.

The control of temperature during the moulding cycle is shown in figure 3, which shows a schematic of an idealised temperature against time profile. At temperatures below T2, which is approximately 90°C for an epoxy resin resinous prepreg laminate assembly, no significant cure advancement or viscosity changes that affect processability occur and the rate of increase of temperature is set at the maximum rate of increase of temperature permissible for the autoclave. During the initial portion of the cycle, in region A, up to the time that temperature T1 is reached, the system response time is measured. The system response time is of the order of several minutes, for example 5 to 10 minutes. The calculator 42 predicts the course of the reaction for future time periods equal to the system response time at 1 minute intervals. This frequency of prediction ensures that no catastrophe will occur at any time which cannot be corrected by adjustments to the temperature in the autoclave.

At temperature T2 the rate of increase of temperature is decreased so that the temperature gradients throughout the resinous prepreg laminate assembly is minimised by the time the average temperature reaches T3, approximately 115°C for an epoxy resin resinous prepreg laminate assembly.

At temperature T3 the resin viscosity approaches values, below 1000 Poise, at which significant resin flow can occur. The rate of increase of temperature between T3 and T4 is governed by conflicting rules which aim to maximise the available time for resin flow. Temperature T4 is approximately 130° for an epoxy resin resinous

prepreg laminate assembly. Some rules attempt to minimise the resin viscosity by accelerating the rate of increase of temperature. Other rules attempt to prolong the time at which the system remains at minimum viscosity conditions. These rules are operative until the viscosity exceeds 1000 Poise.

Between temperatures T3 and T6 the exothermic reaction due to advancing resin cure accelerates and rules limiting control temperature tolerances of increasing severity, proportional to the exotherm acceleration are operative. Temperature T6 is approximately 160°

Between temperatures T6 and T7 the exotherm decelerates and control is relaxed but rules are still operative to ensure limitation of any residual exotherm that may occur. Temperature T7 is the full post cure temperature which is 190°C for an epoxy resin resinous prepreg laminate assembly.

The control of pressure during the moulding cycle is shown in figure 4, which shows a schematic of an idealistic pressure against time profile. At temperatures below 120°C no significant resin flow must occur out of the resinous prepreg laminate assembly because below this temperature the latent particulate hardener in the resin is not fully in solution. Filtration of the hardener particles would occur if flow were present and this would lead to non-homogeneous cure The pressure P1 up to this temperature is maintained at a level sufficient for modest compaction of the resinous prepreg laminate assembly in order to optimise heat transfer. The pressure P1 is 30 pounds per square inch.

Between pressures P1 and P2 the pressure is controlled in such a manner to maximise the depth within the resinous prepreg laminate assembly from which resin flow occurs and to ensure that adequate flow does occur. The pressure is increased in steps when the reaction occurs to ensure the resin flows out by ensuring that the

resinous prepreg laminate assembly is not over compressed.

The pressure P2 is reached either when the viscosity of the resin becomes greater than 1000 Poise at which value flow is considered minimal, or when the bleed pack is filled. The pressure thereafter is increased at maximum rate up to the maximum consolidation pressure P3 for residual void collapse. Pressure P3 is 200 pounds per square inch.

The control system of the present invention at discrete times during the process uses mathematical models to perform two basic tasks. The control system firstly determines the current state of the resinous prepreg laminate assembly temperature distribution and the physical properties such as laminate thickness, Vf distribution and bleed pack filling. The control system secondly uses the information on the current state of the resinous prepreg laminate assembly temperature distribution to predict the consequences if the process were to proceed at a number of rates of increase of temperature for a time exceeding the system response time. The control system then selects the highest rate of increase of temperature, which does not adversely effect the properties of the resulting composite material article, for the next future time period of 60 seconds and applies this rate of increase of temperature to the resinous prepreg laminate assembly for 60 seconds.

If a thermocouple or other temperature sensor is located in the mould, resinous prepreg laminate assembly or gas within the autoclave the actual temperature may be measured. These measured values of temperature may be compared with the predicted, calculated, values of temperature for that, or those, particular positions to ensure that there is no difference, or that the difference is within a predetermined range to check that the rules are accurate. The comparison is performed at every 60 second time interval prior to selection of the

maximum possible rate of increase of temperature.

The operator initially enters details into the control computer 34 to enable the control computer 34 to perform the calculations i.e. the operator enters the number of layers of material in the resinous prepreg laminate assembly, the thickness of the layers, the type of resinous prepreg laminate assembly, the material from which the mould is made, i.e its conductivity, the number of layers of glass cloth in the bleed pack etc.

Another parameter entered into the control computer 34 is the type of resin. Thus for the prepreg laminate assembly the details of the fibre density, the resin density, the prepreg weight per unit area, the fibre weight per unit area and the permeability are entered. For the bleed pack the type of glass cloth, the weight of the glass cloth per unit area and its permeability.

Figures 5A to 5F indicate the temperatures and pressures applied to the resinous prepreg laminate assembly and the effects on resin flow rate, fibre content, fractional cure and viscosity for a steel mould 15 mm thick, a resinous prepreg laminate assembly with 50 layers of carbon fibre cloth/epoxy resin and a bleed pack with 32 layers of glass cloth for resin absorption. Curve C1 in figure 5A shows the temperature/time profile of the autoclave gas, and curve C2 shows the temperature/time profile of the mid laminate in the resinous prepreg laminate assembly. Curve C1 illustrates the effect of the control rules on the processing cycle, and curve C2 indicates that the temperature of the mid laminate of the resinous prepreg laminate assembly never exceeded the autoclave gas temperature significantly at any time during the process and that the exothermic heat was dissipated successfully at all times. The resin viscosity, as shown by curve C3 in figure 5B, remained below a level of 200 Poise for a period of approximately 50 minutes and reached a lower limit of approximately 120 Poise in this interval, thus providing adequate time for

resin flow to occur. The maximum resin flow rate, as illustrated by curve C5 in figure 5D, occurred in the interval when the resin viscosity was below 200 Poise. Curve C6 in figure 5E shows the pressure applied. The increase in the mean fibre volume fraction, as shown by curve C7 in figure 5F, in the resinous prepreg laminate assembly due to compaction is shown as a change from 0.53 to 0.57. The curve C4 in Figure 5C shows the fractional curve. The whole consolidation process took around 270 minutes.

Figures 6A to 6F indicate the temperatures and pressures applied to the resinous prepreg laminate assembly and the effects on resin flow rate, fibre content, fractional cure and viscosity for a ceramic mould 15 mm thick, a resinous prepreg laminate assembly with 50 layers of carbon fibre cloth/epoxy resin and a bleed pack with 32 layers of glass cloth for resin absorption. Curve D1 in figure 6A shows the temperature/time profile of the autoclave gas, and curve D2 shows the temperature/time profile of the mid laminate in the resinous prepreg laminate assembly. Curve D1 illustrates the effect of the control rules on the temperature applied, and curve D6 indicates the effect of the control rules on the pressure applied. Curve D2 shows that the temperature of the mid laminate of the resinous prepreg laminate assembly never exceeded the autoclave gas temperature significantly at any time during the process and that the exothermic heat was dissipated successfully at all times.

On comparing figure 6A with figure 5A it is noted that the mould response to gas temperature changes is more sluggish for the ceramic mould than the steel mould due to the thermal conductivity of the the ceramic mould being lower than the steel mould. The dissipation of heat from the resinous prepreg laminate assembly is also lower for the same reason, with the result that a slightly higher temperature rise due to the reaction

exotherm is evident as the process proceeds.

The faster rise in temperature results in both the resin flow rate reaching a maximum value sooner for the ceramic mould i.e. 103.8 minutes for the ceramic mould compared to 139.4 minutes for the steel mould and also faster filling of the bleed pack for completion of the consolidation cycle.

It is clear that the control system of the present invention produces unique temperature and pressure control conditions which are automatically generated dependent upon physical, material and lay-up thickness characteristics. Although the same control rules are applied it is seen that by their application to the control of temperature and pressure the resinous prepreg laminate assembly is deemed satisfactorily moulded to within acceptable fibre volume fraction tolerance limits for both of the two examples.

The control computer has a prediction time which is less than the real time processing of the resinous prepreg laminate assembly. It is possible to arrange for the control computer to directly apply the calculated rates of increase of temperature and pressure on the autoclave at every minute of the consolidation process. It is equally possible for the control computer to print out, display or otherwise indicate the rates of increase of temperature and pressure at every minute of the consolidation and an operative may then manually apply these settings to the autoclave.

The invention has been described with reference to the autoclave process of manufacture, but the invention is equally applicable to the pressclave process and the compression, or matched die, process. In the compression process the bleed pack, breather and rubber membrane are replaced by a second former. The resinous prepreg laminate assembly is placed between the two formers. The formers may be steel, ceramic etc. It is necessary to adjust the resin flow model to take account of the

outflow of resin from between the dies rather than into the bleed pack. It is also necessary to change the thermal properties of the bleed pack, breather layer and rubber sheet to be equivalent to those of the second former. However, the same rules apply to the compression process.

The invention has been described with reference to the production of fibre reinforced resin matrix composites particularly carbon fibre reinforced epoxy resin matrix composites. The invention may also be applied to the production of composites using other suitable reinforcing fibres and other types of resin. The invention may also be applied to the production of resins reinforced with paper, paper is a fibrous material.

The control computer is arranged with a recorder 54 and a device 56 to display or print the details of the consolidation cycle used for each particular article produced, for example this may be graphically as in figures 5A to 5F or 6A to 6F. The control computer is also arranged to indicate to an operative whether an article which has only had part of the consolidation cycle applied to it, due to a breakdown in the consolidation process for example because of breakdown of heaters or pumps or due to pressure loss from the autoclave, is usable, recoverable is unusable or unrecoverable. By recoverable is meant that it may be reconsolidated.

An advantate of the invention is that it eliminates the need for costly experimentation which is usually necessary for each unique resinous prepreg laminate lay-up to be consolidated.

Because the control computer has mathematical models to predict the course of the consolidation cycle up to and beyond a time at which the system responds to imposed changes then the number of control rules for avoidance of catastrophic events is minimised.

A further advantage is that there is an auditable control of the consolidation cycle which is necessary if total quality is to be maintained in the manufacture of composite material articles.

The invention may be used to produce composite material component for gas turbine engines, for example fan blades, compressor blades, compressor or vanes casings. The invention may also be used to produce other composite material articles.

Claims:-

1. A method of controlling the c nsolidation of a resinous prepreg laminate assembly to produce a composite material article comprising:-

(a) applying heat, at a predetermined rate of increase of temperature, to the resinous prepreg laminate assembly and calculating the time taken for the temperature to increase at a plurality of positions in the resinous prepreg laminate assembly, selecting the greatest calculated time as the system response time or calculating the time taken for the temperature to increase at a position at, or near, the centre of the resinous prepreg laminate assembly, selecting the calculated time as the system response time,

(b) providing mathematical models of the behaviour of at least some of the critical process variables as functions of time, and/or as functions of temperature and/or as functions of other critical process variables,

(c) providing rules to control the application of heat to the resinous prepreg laminate assembly,

(d) calculating the temperature distribution, the amount of resin cure, the viscosity of the resin, the rate of heat generation due to reaction at each of the plurality of positions throughout the resinous prepreg laminate assembly and the amount of consolidation of the resinous prepreg laminate assembly due to outflow of resin, at successive ones of a first series of time intervals having a first predetermined duration, using the mathematical models in (b),

(e) determining the rate of increase of temperature to be applied to the resinous prepreg laminate assembly for a future time interval having a second predetermined duration, at successive ones of a second series of time intervals having a third predetermined duration, using the data collected in step (d), the mathematical models in step (b) and the rules in step (c), wherein the second predetermined duration is greater than the first

predetermined duration, the third predetermined duration is greater than the first predetermined duration, and the system response time is greater than either the second predetermined time interval or the third predetermined time interval,

(f) predicting the course of the process for a future time interval equal to the system response time for a plurality of selected rates of increase of temperature,

(g) discarding any selected rates of increase of temperature, which are predicted to produce unacceptable temperature increases, temperature distributions, viscosities and consolidation,

(h) selecting the highest rate of increase of temperature which is predicted to produce acceptable temperature increases, acceptable temperature distributions, acceptable viscosities and acceptable consolidation,

(i) applying the selected highest rate of increase of temperature to the resinous prepreg laminate assembly for a time interval having the second predetermined duration, which highest rate of increase of temperature is predicted to produce acceptable temperature increase, acceptable temperature distributions, acceptable viscosities and acceptable consolidation for a next future time interval equal to the system response time, at successive ones of the second series of time intervals.

2. A method as claimed in claim 1 wherein the first predetermined duration is 6 seconds.

3. A method as claimed in claim 1 or claim 2 wherein the second predetermined duration is 60 seconds.

4. A method as claimed in claim 1, claim 2 or claim 3 wherein the third predetermined duration is 60 seconds.

5. A method as claimed in any of claims 1 to 4 wherein the resinous prepreg laminate assembly being cured contains carbon fibres.

6. A method as claimed in any of claims 1 to 5 wherein the resinous prepreg laminate assembly being cured contains an epoxy resin.

7. A method as claimed in any of claims 1 to 6 comprising measuring the temperature at at least one predetermined position in the resinous prepreg laminate assembly.

8. A method as claimed in any of claims 1 to 6 wherein the resinous prepreg laminate assembly is placed upon a mould, measuring the temperature at at least one predetermined position in the mould.

9. A method as claimed in any of claims 1 to 6 wherein the resinous prepreg laminate assembly is placed in an autoclave, measuring the temperature of the gas within the autoclave.

10. A method as claimed in any of claims 7 to 9 comprising comparing the measured temperature with the calculated temperature at successive ones of the second series of time intervals prior to selection of the highest rate of increase of temperature to the resinous prepreg laminate assembly, determining if any difference between the measured temperature and the calculated temperature is within a predetermined range to check that the rules are accurate.

11. A method as claimed in any of claims 1 to 10 comprising applying sufficient pressure to the resinous prepreg laminate assembly to maintain thermal contact for efficient heat transfer until the reaction occurs, increasing the pressure applied to the resinous prepreg laminate assembly in steps to cause the resin to flow out of the resinous prepreg laminate assembly when the reaction occurs.

12. A method as claimed in claim 11 comprising measuring the pressure applied on the resinous prepreg laminate assembly at at least one predetermined position in the resinous prepreg laminate assembly.

13. A method as claimed in claim 11 wherein the resinous

prepreg laminate assembly is placed in an autoclave, measuring the pressure of the gas within the autoclave.

14. A method as claimed in claim 12 or claim 13 comprising comparing the measured pressure with the calculated pressure at successive ones of the second series of time intervals prior to selection of the highest rate of increase of pressure to the resinous prepreg laminate assembly, determining if any difference between the measured pressure and the calculated pressure is within a predetermined range to check that the rules are accurate.

15. A method of controlling the consolidation of a resinous prepreg laminate assembly to produce a composite material article substantially as hereinbefore described with reference to the accompanying drawings.

16. An apparatus for controlling the consolidation of a resinous prepreg laminate assembly to produce a composite material article comprising:-

pressing means to apply a pressure on the resinous prepreg laminate assembly,

heating means to heat the resinous prepreg laminate assembly,

a control computer having means to calculate the time taken for the temperature to increase at a plurality of positions in the resinous prepreg laminate assembly from the commencement of application of heat on the resinous prepreg laminate assembly, or to calculate the time taken for the temperature to increase at a position at, or near, the centre of the resinous prepreg laminate assembly,

the control computer having means to select the greatest calculated time as the system response time, or to select the calculated time as the system response time,

the control computer having mathematical models of the behaviour of at least some of the critical process variables as functions of time, and/or as functions of

temperature and/or as functions of other critical process variables,

the control computer having rules to control the application of heat to the resinous prepreg laminate assembly,

the control computer having means for calculating the temperature distribution, the amount of resin cure, the viscosity of the resin, the rate of heat generation due to reaction at each of the plurality of positions throughout the resinous prepreg laminate assembly and the amount of consolidation of the resinous prepreg laminate

assembly due to outflow of resin, at successive ones of a first series of time intervals having a first predetermined duration, using the mathematical models,

the c ntrol computer having means to determine the rate of increase of temperature to be applied to the resinous prepreg laminate assembly for a future time interval having a second predetermined duration, at successive ones of a second series of time intervals having a third predetermined duration, using the calculated values of temperature distribution, the amount of resin cure, the viscosity of the resin, the rate of heat generation at each of the positions in the resinous prepreg laminate assembly and the amount of consolidation, the mathematical models and the rules, the second predetermined duration is greater than the first predetermined duration, the third predetermined duration is greater than the first predetermined duration, and the system response time is greater than either the second predetermined time interval or the third predetermined time interval,

the control computer having means for predicting the course of the process for the next future time interval equal to the system response time for a plurality of selected rates of increase of temperature, the control computer having means to discard any selected rates of increase of temperature which are predicted to produce

unacceptable temperature increases, temperature distribution, viscosities and consolidation, the control computer having means for selecting the highest rate of increase of temperature which is predicted to produce acceptable temperature increases, acceptable temperature distributions, acceptable viscosities and acceptable consolidation of the resinous prepreg laminate assembly,

the control computer having means for sending a signal to the heating means to apply the selected highest rate of increase of temperature to the resinous prepreg laminate assembly for the next future time interval equal to the second predetermined duration at successive ones of the second series of time intervals.

17. An apparatus as claimed in claim 16 in which at least one temperature sensor is located at a predetermined position in the resinous prepreg laminate assembly, means to supply temperature signals from the at least one temperature sensor to the control computer during the curing process.

18. An apparatus as claimed in claim 16 in which the resinous prepreg laminate assembly is placed upon a mould, at least on temperature sensor is located at a predetermined position in the mould, means to supply temperature signals from the at least one temperature sensor to the control computer during the curing process.

19. An apparatus as claimed in claim 16 in which the resinous prepreg laminate assembly is placed in an autoclave, at least one temperature sensor is located in the autoclave to measure the temperature of a gas in the autoclave, means to supply temperature signals from the at least one temperature sensor to the control computer during the curing process.

20. An apparatus as claimed in any of claims 17 to 19 in which the control computer has means for comparing the measured temperature with the calculated temperature at every third predetermined duration prior to selection of the highest rate of increase of temperature to the

resinous prepreg laminate assembly, the comparing means determines if any difference between the measured temperature and the calculated temperature is within a predetermined range to check that the rules are accurate.

21. An apparatus as claimed in any of claims 17 to 20 in which there are a plurality of temperature sensors.

22. An apparatus as claimed in any of claims 17 to 21 in which the at least one temperature sensor is a thermocouple.

23. An apparatus as claimed in any of claims 16 to 22 in the pressing means applies sufficient pressure to the resinous prepreg laminate assembly to maintain thermal contact for efficient heat transfer until the reaction occurs, and increases the pressure applied to the resinous prepreg laminate assembly in steps to cause the resin to flow out of the resinous prepreg laminate assembly when the reaction occurs.

24. An apparatus as claimed in claim 23 in which there is at least one pressure sensor at a predetermined position in the resinous prepreg laminate assembly, means to supply pressure signals from the at least one pressure sensor to the control computer during the curing process.

25. An apparatus as claimed in claim 23 in which the resinous prepreg laminate assembly is placed in an autoclave, at least one pressure sensor is placed in the autoclave to measure the pressure of the gas in the autoclave, means to supply pressure signals from the at least one pressure sensor to the control computer during the curing process.

26. An apparatus as claimed in claim 24 or claim 25 in which the control computer has means for comparing the measured pressure with the calculated pressure at every third predetermined time period prior to selection of the highest rate of increase of pressure to the resinous prepreg laminate assembly, determining if any difference between the measured pressure and the calculated pressure is within a predetermined range to check that the rules

are accurate.

27. An apparatus as claimed in any of claims 16 to 26 in which the pressing means comprises means to supply pressurised gas.

28. An apparatus as claimed in any of claims 16 to 27 including means to record the temperature applied to the resinous prepreg laminate assembly during the consolidation cycle.

29. An apparatus as claimed in any of claims 16 to 28 including means to display or print the temperature applied to the resinous prepreg laminate assembly during the consolidation cycle.

30. An apparatus for controlling the consolidation of a resinous prepreg laminate assembly to produce a composite material article substantially as hereinbefore described with reference to and shown in figures 1 and 2 of the accompanying drawings.

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Databases (see below)
(i) UK Patent Office collections of GB, EP, WO and US patent specifications.

(ii)

Documents considered relevant following a search in respect of Claims :-
1 TO 30

Categories of documents

X: Document indicating lack of novelty or of inventive step.

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P: Document published on or after the declared priority date but before the filing date of the present application.

E: Patent document published on or after, but with priority date earlier than, the filing date of the present application.

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Category	Identity of document and relevant passages	Relevant to claim(s)
A	EP 0074868 A1 (LA TELEMICANIQUE ELECTRIQUE)	

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